

MOONAGE DAYDREAM: REASSESSING THE SIMPLE MODEL FOR LUNAR MAGMA OCEAN CRYSTALLIZATION. J.F. Rapp¹ and D.S. Draper², ¹Jacobs, NASA Johnson Space Center, Houston, TX 77058 (jennifer.f.rapp@nasa.gov), ²NASA Johnson Space Center, Houston, TX 77058.

Introduction: Details of the differentiation of a global-scale lunar magma ocean (LMO) remain enigmatic, as the Moon is not simply composed of highlands anorthosite and a suite of mare basalts as inferred from early studies. Results from recent orbital missions, and the increasingly detailed study of lunar samples, have revealed a much larger range of lithologies, from relatively MgO-rich and “purest anorthosite” discovered on the lunar far side by the M³ instrument on Chandrayaan-1 [1] to more exotic lithologies such as Si-rich domes [2] and spinel-rich clasts [3,4] distributed globally. To understand this increasingly complex geology, we must understand the initial formation and evolution of the LMO, and the composition of the cumulates this differentiation could have produced. Several attempts at modelling such a crystallization sequence have been made [5-7], and have raised as many questions as they have answered.

We present results from our ongoing experimental simulations of magma ocean crystallization, investigating two end-member bulk compositions (TWM [8] and LPUM [9]) under fully fractional crystallization conditions. These simulations represent melting of the entire silicate portion of the Moon, as an end-member starting point from which to begin assessing the evolution of the lunar interior and formation of the lunar crust.

Experimental: Starting compositions were synthesized from mechanical mixtures of anhydrous oxides. Experiments were performed in Depths of the Earth QuickPress piston cylinders at NASA Johnson Space Center, under nominally anhydrous conditions using graphite capsules and BaCO₃ as a pressure medium. As this study aims to simulate crystallization from a magma ocean by cooling, experimental charges were heated to a superliquidus temperature before dropping to the temperature of interest. Experiments were held at temperature for up to 72, and quenched by cutting the power to the assembly. Run products were analyzed by electron microprobe at 15kV and 20nA using a 10 µm defocused beam on the glass phase.

In order to simulate fractional crystallization, experiments with approximately 10% crystallization were targeted. The composition of the glass from each step was used as the starting composition for the next set of experiments, simulating 10% fractionation of crystals from melt. At each stage the total volume crystallized was calculated, and this value was used to calculate the pressure appropriate for the next set of experiments. Pressures below 0.5 GPa cannot be achieved in the JSC

piston-cylinders, and so low pressure experiments were run in Deltech CO-CO₂ gas mixing furnace buffered at IW.

Results: The full fractional crystallization sequence is complete in the LPUM composition, and 74% complete in the TWM composition. A weighted average of the cumulate pile composition based on modal abundance of each phase, taking into account the changing composition of a given mineral as fractionation progresses, has been calculated, and is within 5% of the LPUM starting composition, indicating mass balance throughout the experimental sequence. The experimentally derived LMO (Fig. 1) is characterized by the predomination of olivine early in the crystallization sequence. Olivine is the only crystallizing phase for the first 50% of LMO crystallization in both bulk compositions.

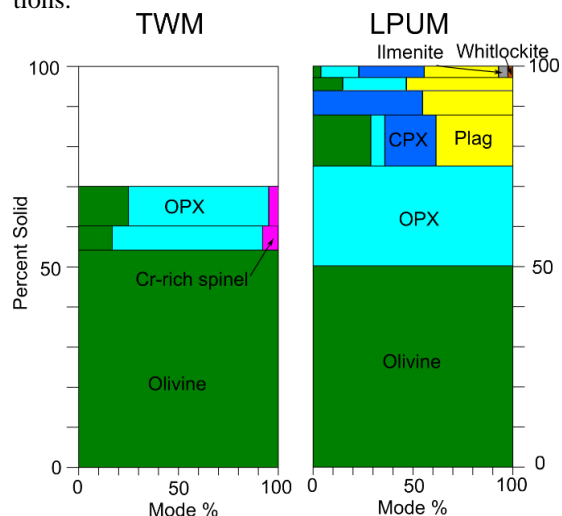


Figure 1: Experimental results of fractional crystallization experiments on two LMO bulk compositions.

After 50% crystallization, the liquidus phase switches to low-Ca pyroxene in the LPUM composition, whereas both low-Ca pyroxene and Cr-rich spinel co-crystallize with olivine in the TWM composition. At 75% crystallization plagioclase becomes a liquidus phase in the LPUM composition, but at 74% crystallization in TWM (the highest degree of crystallinity yet explored), plagioclase is not present, despite having more Ca and Al in the bulk composition than does LPUM. The LPUM cumulate pile consists of approximately 10.5% modal plagioclase, which corresponds to a crustal thickness of approximately 60km.

Discussion: The experimental results indicate that neither end-member bulk composition will produce a

cumulate pile with plagioclase abundance that is proportional to a crustal thickness of 45 km or less. LPUM produces plagioclase abundance consistent with a crust of ~ 60km, and although experiments on TWM are not complete, we expect it to produce a thicker layer of anorthosite due to the enrichment of refractory elements in this composition – the higher abundance of Ca and Al were initially proposed to account for a crust of up to 100 km depth. However, our model does not take into account trapped interstitial liquid. [6] showed that increasing the amount of trapped interstitial liquid in their model decreases the amount of anorthosite in the final cumulate pile as Al-rich liquid is sequestered in the mantle. Furthermore, the depth of the magma ocean and the mode of crystallization are important factors in the amount of plagioclase produced. A shallower magma ocean would likely stabilize plagioclase earlier in the sequence, as it the major aluminous phase stable at low pressure. At higher pressures plagioclase crystallization is suppressed, and Al-rich pyroxenes, spinel and eventually garnet are stabilized. There is evidence of this in the experimentally produced TWM cumulates, which contain a spinel-structure phase which is a solid solution between chromite (FeCr_2O_4) and spinel (MgAl_2O_4) from 55 – 70% crystallization (~1.5 – 1 GPa).

Alternative LMO crystallization models. As alluded to above, several groups advocate for a shallower magma ocean rather than full mantle melting [e.g. 10], despite evidence suggesting the heat flow involved in accretion would be more than enough to account for whole Moon melting [9,11]. Given the stability of plagioclase over other aluminous phases at lower pressure however, a shallower magma ocean would likely increase the thickness of the plagioclase crust produced.

Another alternative model for LMO crystallization is that of a period of equilibrium crystallization, in which crystals remain entrained in the magma, followed by fractional crystallization after a critical melt viscosity is reached [12]. This two-step approach will produce a less extreme fractionation of the magma, and potentially somewhat less plagioclase, and therefore could be a preferred mechanism for LMO crystallization. Computational models by [5] have been the framework for LMO crystallization in the lunar community, but experimental work by [13] called some of the conclusions into question.

Although experimental work on the fractional part of LMO crystallization following initial equilibrium crystallization by [13] are ongoing, the MELTS algorithms [14,15] allow us to investigate the likely crystallization sequence for a residual liquid after 50% equilibrium crystallization. There are limitations to using MELTS, and there is a lack of experimental data to calibrate the model for calculations at the P,T,x appropriate

to LMO crystallization. Nevertheless it provides a useful tool to investigate crystallization sequences before embarking on a full experimental program. We performed fractional crystallization calculations on the LPUM 50% residual liquid from [13] at 2, 1, 0.5 GPa and 1-bar to simulate different depths of magma ocean. Plagioclase is present only in the calculations at < 1 GPa, and forms approximately 10% of the cumulate pile – similar to our experimental outcomes. The next step is to carry out a polybaric fractionation sequence, as at higher pressures garnet is stabilized. The geochemistry of some lunar basalts suggests that garnet is residual in their source region [16]. Experimental work to date has failed to produce significant garnet in cumulates at an appropriate depth for basalt source regions, but crystallization under hybrid equilibrium/fractional conditions at higher pressure could allow for garnet crystallization, which would lead in turn to less plagioclase crystallization, consistent with a thinner anorthosite crust. Although further experimental and sample work is necessary, it is becoming increasingly clear that a simple model of LMO crystallization is no longer adequate to explain lunar geology.

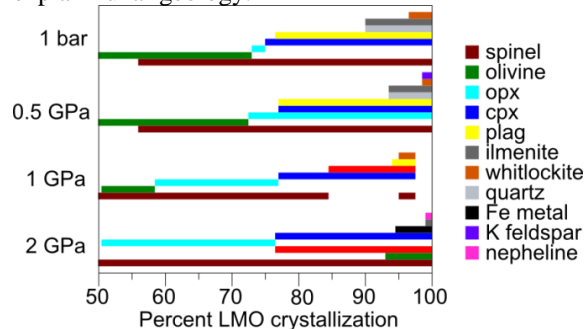


Figure 2: MELTS model outcomes of fractional crystallization of the residual liquid after 50% equilibrium crystallization of LPUM [13].

References: [1] Ohtake M. et al. (2012) *Nat Geo.* **5**, 384-388. [2] Jolliff B. et al. (2011) *Nat. Geo.* **4**, 566-571 [3] Gross J. et al. (2014): *Am. Min.* **99**, 1849-1859. [4] Prissell T. C. et al. (2014) *EPSL* **403**, 144-156 [5] Snyder G. A. et al. (1992) *GCA.* **56**, 3809-3823 [6] Elkins-Tanton L. T. et al. (2011) *EPSL* **304**, 326-336. [7] Davenport J.D. et al. (2014) *LPSC* 45, #1111. [8] Taylor, S.R., (1982) *Planetary Science, a Lunar Perspective*. [9] Longhi, J., (2006) *GCA* **70**, 5919. [10] Charlier B. et al. (2015) *LPSC* 46, #1168 [11] Canup R. M. & Asphaug E. (2001) *Nature* **412**, 708-712. [12] Tonks, W.B. and Melosh H. J., (1990) *Origin of the Earth*. [13] Elardo, S.M., et al. (2011), *GCA* **75**: 3024. [14] Smith P.M. & Asimow P. D. (2005) *G³*, doi:[10.1029/2004GC000816](https://doi.org/10.1029/2004GC000816). [15] Ghiorso M. S. & Sack R. O. (1995) *CMP* **119**(2), 197-212. [16] Neal C. R. (2001) *JGR* **106**(E11), 27865-27885